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Soil temperature increase in eastern Australia for the past 50 years

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ABSTRACT

Traditionally, soil temperatures at various depths were measured daily at agricultural research stations around the world. Short-term fluctuations are damped at depth, acting as a natural low pass filter on soil surface temperature time series. In the last 20 years, a number of northern hemisphere soil temperature data sets have been analysed for long term trends, but our analysis at four sites in eastern Australian is the first in the southern hemisphere. Soil temperature data at Cowra in New South Wales, Australia was recorded daily at 09.00 at a depth of 1.8 m from 1942 to 2010, together with rainfall and maximum and minimum air temperature data. From 1972 temperatures at some shallower depths were also recorded. We found significant average annual temperature rises in soil and air temperature data, with greater rises in the soil temperatures over this period. We also analysed soil and air temperature data recorded from 1970 at Gunnedah, Inverell and Brigalow in eastern Australia. To standardise for soil temperature measurements taken at various depths, we proposed a model that estimated the rise of the ground surface temperature accounting for the attenuation and delay of the surface temperature signal with depth. We estimated the rise of the soil surface temperature Cowra from about 1970 as 0.06 K year^{-1}. We found the rate of rise of the average of the daily maximum and minimum air temperatures to be 0.022 K year^{-1}. For Gunnedah, Inverell, and Brigalow, from 1970 the rates of rise of soil temperatures at 1 m and air temperatures were at around 0.02 K year^{-1}. These soil temperature data show a clear warming trend overall since about 1970.

1. Introduction

Historically, soil temperature data have been measured and recorded mainly for agricultural applications, and to study the way diurnal and seasonal variations are propagated (Watson, 1980). Lambert (1779) in Germany and Forbes (1846) at Edinburgh in Scotland published time series of measurements of soil temperature at various depths. Thomson (1861) presented the theory of soil temperature change in response to periodic surface temperature variations, and Everett (1861) carried out Fourier analysis on the data of Forbes. He used the predicted variation of both attenuation and phase lag with depth for annual waves to estimate the soil thermal diffusivity.

Many research stations around the world that recorded weather data also recorded soil temperature at one or more depths. In Australia, it is commonly measured daily at 09.00. Over the last two decades some of this long-term data has been analysed for trends which may be evidence of climate change. The greater the measurement depth, the more short term fluctuations are filtered out and missing data can be more accurately interpolated. Northern hemisphere long term soil temperature data sets have been analysed by Baker and Ruschy (1993), Changnon (1999), Zhang et al. (2001), Baker and Baker (2002), Hu and Feng (2003), Zhang et al. (2005), García-Suárez and Butler (2006), Isard et al. (2007), Du et al. (2007a, 2007b), Pokladnikova et al. (2008), Subedi and Fullen (2009), Jacobs et al. (2011), Qian et al. (2011), You et al. (2013), Bai et al. (2014), Yeşilırmak (2014) and Cheon et al. (2014). These authors have found increase in soil temperature which is associated with climate change (Table 1).

Soil temperature in Australia has been investigated for temperature regime classification according to the US Soil Taxonomy (Watson, 1980), for crop and pasture management (Horton and Corkrey, 2011), and modelling at a catchment scale (Kunkel et al., 2016). However, to the best of our knowledge, no long-term soil temperature trend has been analysed in the southern hemisphere. In this paper, we analyse long-term trend of soil temperature data from four sites in eastern Australia with an objective is to estimate increase in soil temperature from the past 40 years.

Meteorological observations at the research station at Cowra, Australia, is unique as it recorded soil temperature at a depth of about 1.8 m daily at 09.00 from 1942 to 2010. Other Australian soil temperature data sets at locations such as Gunnedah, Inverell in New South

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Table 1
A summary of studies evaluating long-term soil temperature changes.

Authors	Location	Period of observations	Depth of soil temperature measurement (m)	Rate of soil temperature rise (C yr^{-1})	MAT[a] (C)	Rate of air temperature rise (C yr^{-1})
Bai et al. (2014)	Mojave Desert, USA	1982–2000	0.5	0.079	19	0.063
Baker and Baker (2002)	St. Paul campus of the University of Minnesota, USA	1963–2000	3.2, 6.4, 12.8	0.045–0.048	7.4	0.049 and 0.035
Changnon (1999)	Rural Illinois, USA	1889–1952	0.91	0.017	11.4	0.028
Hu and Feng (2003)	292 stations from USA	1967–2002	0.1–1.0	0.030		
Schmidt et al., 2001	Fargo, North Dakota, USA	1980–1990	0.01–11.70	0.093	9.4	
Qian et al. (2011)	30 climate stations across Canada	1958–2008	0.05–1.5	0.026–0.03		
Gądek and Leszkiewicz (2012)	Tatra Mountains, Poland and Slovakia	1955–2010	0	0.09–0.13	6–8	
García-Suárez and Butler (2006)	Armagh Observatory, Northern Ireland	1904–2002	0.3, 1.0	0.013		
Jacobs et al. (2011)	Haarweg Station, grassland in the centre of Netherlands	1987–2009	0.05–1.0	0.044	10	0.057
Pokladnikova et al. (2008)	Pohořelice, Poland	1961–2000	0.05–1.0	0.034	9	
Subedi and Fullen (2009)	Hilton Experimental Site, Shropshire, UK	1982–2006	0–1	0.040	12	
Yeşilırmak (2014)	Büyük Menderes Basin, Turkey	1970–2006	0.05–1.0	0.08–0.25		0.003–0.035
Zhang et al. (2001)	Irkutsk, Russia	1898–2005	0.4–2.0	0.02–0.012	− 0.5	0.08
Zhang et al. (2016)	360 sites in China	1962–2011	3.2	0.032		0.03
Cheon et al. (2014)	Seoul, S. Korea	1960–2010	5	0.040	13.3	0.031
Cheon et al. (2014)	Incheon, S. Korea	1960–2010	5	0.020	13.9	0.034
Cheon et al. (2014)	Busan, S. Korea	1960–2010	5	0.029	16.2	0.024
Cheon et al. (2014)	Daejeon, S. Korea	1960–2010	5	0.073	14.2	0.040

[a] MAT is mean annual temperature.

Wales and Brigalow in Queensland start about 1970. We first analyse the Cowra data, and then analyse the shorter Gunnedah, Inverell and Brigalow data sets for comparison. We use the Fourier analysis technique of Everett (1861) and Horton et al. (1983) to calculate the attenuation and phase shift of the annual temperature waves at the various depths to estimate the soil thermal diffusivity. We propose a model based on an analytical solution to calculate the difference between an assumed linear rise of soil surface temperature (SST) and the resultant temperature rise at the depth of 1.8 m. We then assume a linear temperature rise at an unknown rate at the surface, and fit the corresponding calculated temperature rise at 1.8 m to the measured data at that depth, in order to infer the rate of rise of the SST. We compare this to the fitted rates of rise of the annual averages of the measured daily minimum and maximum air temperatures at Cowra. The same procedure is then done for soil temperature measurements from 1970 onwards at 1 m depth at the other sites and the results are compared.

2. Data

The location of the four meteorological stations used in this paper is given in Fig. 1, and their descriptions are given in Table 2. Lang (1973) gave details of meteorological observations at the research station at latitude 33.8 S, longitude 148.7 outside the town of Cowra, Australia, population about 10,000. The Cowra research station is about 3.2 km northeast from the centre of the town and about 1.1 km from the nearest housing development. The meteorological station is above a meteorological lawn and is about 20 m from the nearest trees, which increased in size from 1942 to 2010. Otherwise conditions have remained largely the same, as can be seen by comparing the photograph in Lang (1973) with the present day view from the same position. The soil from a pit nearby (about 200 m) is a Red Chromosol according to the Australian soil classification system (Isbell, 2016) or a Luvisol according to the World Reference Base (IUSS, 2015). The daily minimum and maximum air temperatures at a height of about 1.45 m in a Stevenson screen were measured from mid-1943 to mid-2010, as well as the daily minimum of the terrestrial air temperature (T_{terr}) from a thermometer with a bulb approximately 4 cm above the grass, an approximation for the surface air temperature (SAT). Soil temperature at a depth of 1.83 m was measured daily at 09.00 h from 1942, with the depth later changed to 1.80 m (See Photo P1 in Supplementary materials). The temperature at the deeper soil layers was measured as part of a program to measure the seasonal changes in soil temperature as these might affect the growth of introduced deep rooted perennial grasses. From November 1971 the temperatures at depths of 0.1, 0.2, 0.5 and 1 m, were also measured, and all soil temperature measurements ceased after 2010. There is a small amount of missing data for periods of a few days to about 20 days, and we used linear interpolation to fill all of the gaps.

Fig. 2 shows annual averages of the daily soil temperatures at 9 am at the various depths, plotted against year for Cowra. At 9 am the temperature profile with depth usually has a local maximum at the warming soil surface, decreases to a minimum a few cm below the surface, and then increases with depth. This ‘time of day’ effect causes the annual means of the temperatures measured at 9 am to increase with depth in any given year. Simple moving averages over 9 years at each depth are also plotted, making the temporal trends more obvious by smoothing out short term fluctuations, which are likely due to the El Nino Southern Oscillation (ENSO), which has a period of 3 to 7 years (Kaper and Engler, 2013).

Soil and air temperature data from Gunnedah (31.03 S, 150.27 E) and Inverell (29.77 S, 151.08 E) in New South Wales and Brigalow (24.83 S, 149.80 E) in Queensland were obtained from the Bureau of Meteorology. Soil temperature data were available at depths of 0.1, 0.2, 0.5 and 1 m. Data from Gunnedah is available from 1965 to 2013, Inverell from 1970–2013, Brigalow from 1968–2010. The data for these three sites has longer series of missing values than for Cowra, and so some years still had missing values after the shorter gaps of up to 18 days were filled by linear interpolation. Annual averages were not calculated for those years with long gaps.

3. Periodic surface temperature

The soil has volumetric heat capacity C (in J m^{-3} K^{-1}) and thermal conductivity k (W m^{-1} K^{-1}). The soil temperature is T (z, t) which is

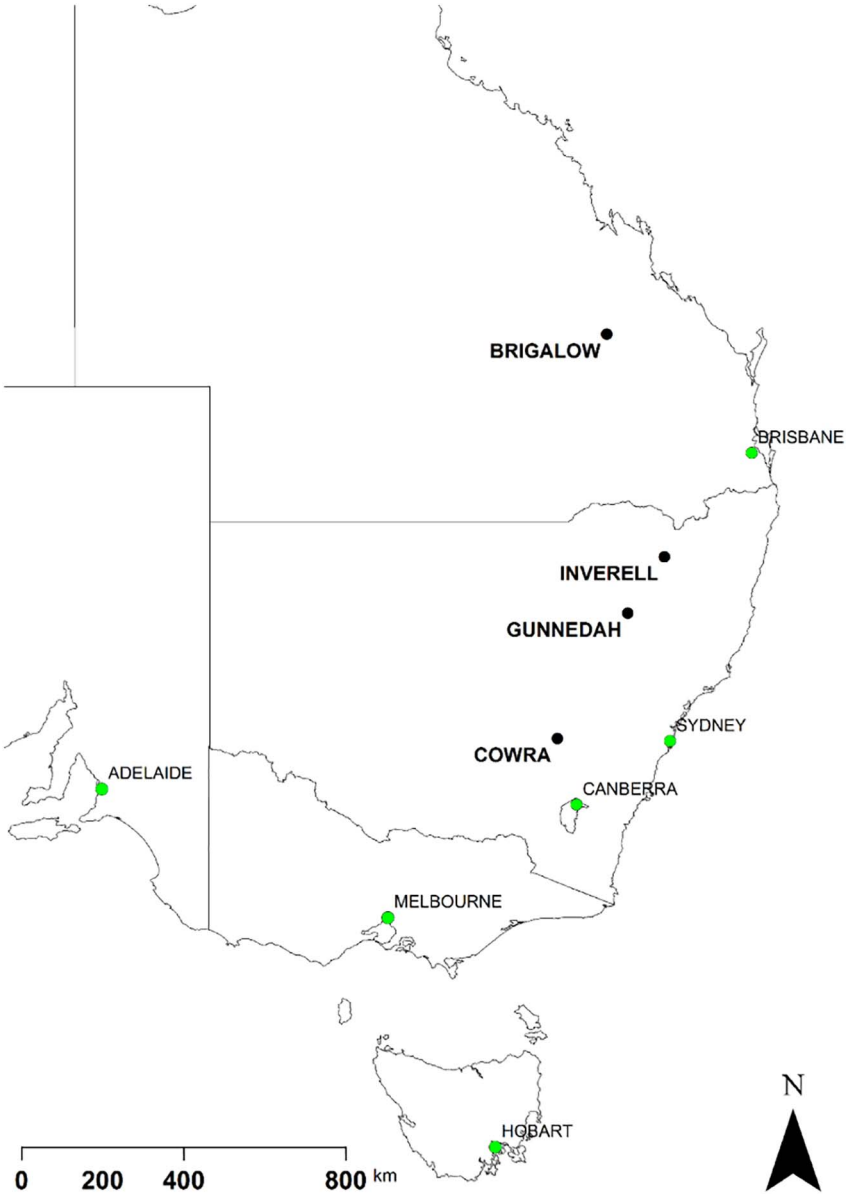

Fig. 1. Locations of the meteorological stations used in this study.

Table 2
Site characteristics of the weather stations used in this study.

Station	Geographical coordinates (latitude, longitude)	Soil type (ASC[a] & WRB[b])	Year of observations	Depth of soil temperature observations (m)	MAP[c] and range (mm)	MAT[d] and range (C)
Cowra, NSW	− 33.8087, 148.7071	Chromosol (ASC), Luvisol (WRB)	1942–2010	1.8 (1942–2010) 0.1, 0.2, 0.5, 1.0 (1971–2010)	630 (221–1140)	16.0 (14.2–17.5)
Gunnedah, NSW	− 31.0261, 150.2687	Vertosol (ASC), Vertisol (WRB)	1965–2013	0.1, 0.2, 0.5, 1.0	633 (296–1014)	18.4 (17.3–19.6)
Inverell, NSW	− 29.7752, 151.0819	Ferralsol (ASC), Paheozem (WRB)	1970–2013	0.1, 0.2, 0.5, 1.0	818 (534–1140)	16.3 (15.6–17.4)
Brigalow, QLD	− 24.8353, 149.8003	Chromosol (ASC), Luvisol (WRB)	1968–2010	0.1, 0.2, 0.5, 1.0	679 (338–1043)	21.4 (20.0–22.4)

[a] ASC = Australian soil classification system (Isbell, 2016).
[b] WRB = World Reference Base (IUSS, 2015).
[c] MAP = mean annual precipitation.
[d] MAT = mean annual temperature.

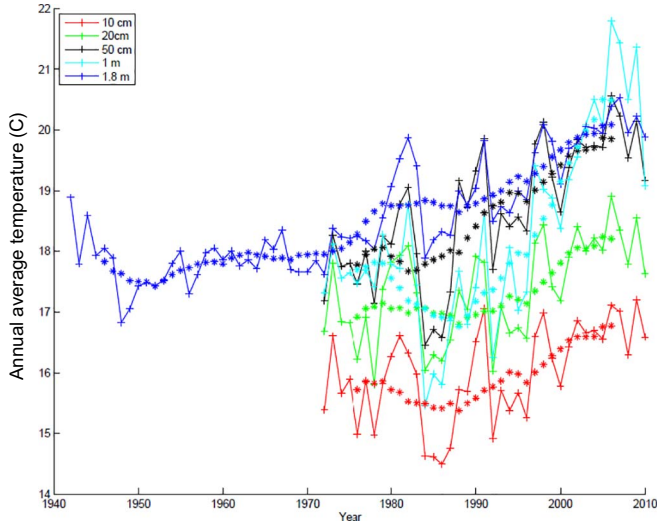

Fig. 2. Annual averages of the daily soil temperatures at 9 am at Cowra at depths 0.1, 0.2, 0.5, 1 and 1.8 m plotted against time in years. Nine year moving averages are also shown as '*' symbol.

assumed to satisfy the one dimensional heat equation

$$C\frac{\partial T}{\partial t} = k\,\frac{\partial^2 T}{\partial z^2}, \tag{1}$$

where t (s) is time and z (m) is the depth below the soil surface. The ratio $\kappa = k/C$ ($m^2\,s^{-1}$) is the soil thermal diffusivity. The theory of the propagation of periodic soil temperature waves was given by Thomson (1861) and is described in Carslaw and Jaeger (1959). Everett (1861) used a version of the Fast Fourier Transform to harmonically analyse the temperature data at various depths, and used the attenuation and phase shift of the temperature waves with depth to estimate the soil thermal diffusivity. Horton et al. (1983) and Elias et al. (2004) further presented methods for estimating apparent thermal diffusivity from field-measured values of soil temperature.

If the soil surface temperature has the steady periodic variation

$$T_n(0,t) = a_n \cos\left(\frac{2\pi nt}{P} - \epsilon_n\right) \tag{2}$$

where n is a positive integer, P/n is the period, a_n is the amplitude and ϵ_n is the phase lag, then the steady periodic variation in soil temperature at a depth z is

$$T_n(z,t) = a_n \cos\left(\frac{2\pi nt}{P} - \lambda_n z - \epsilon_n\right)\exp\left(-\lambda_n z\right) \tag{3}$$

with the quantity

$$\lambda_n = \sqrt{\frac{n\pi}{\kappa P}} \tag{4}$$

determining the rate of attenuation and phase shift with depth. It also determines the sinusoidal surface variation. Conversely, if we observe a periodic soil temperature $T(z, t)$ with period P at a depth z, then we can use the theory of Fourier series to decompose it as

$$T(z,t) = c_0(z) + \sum_1^\infty \left[c_n(z)\,cos\left(\frac{2\pi nt}{P}\right) + d_n(z)\,sin\left(\frac{2\pi nt}{P}\right)\right], \tag{5}$$

with the average temperature at that depth given by

$$c_0(z) = \frac{1}{P}\int_0^P T(z,t)dt, \tag{6}$$

and for $n > 0$

$$c_n(z) = \frac{2}{P}\int_0^P T(z,t)\cos\left(\frac{2\pi nt}{P}\right)dt, \tag{7}$$

$$d_n(z) = \frac{2}{P}\int_0^P T(z,t)\sin\left(\frac{2\pi nt}{P}\right)dt. \tag{8}$$

Following Everett (1861), the amplitude A_n of the nth component of the wave at a depth z is

$$A_n(z) = \sqrt{c_n^2 + d_n^2}. \tag{9}$$

The phase shift ϕ_n of the n-th component satisfies

$$tan\left[\phi_n(z)\right] = d_n/c_n. \tag{10}$$

Then two estimates of the soil thermal diffusivity κ are obtained from the reduction of the amplitude $A_n(z)$ and the difference of the phase shift $\phi_n(z)$ at two depths z_1 and z_2:

$$\lambda_n = \sqrt{\frac{n\pi}{\kappa P}} = \frac{\log[A_n(z_1)] - \log[A_n(z_2)]}{z_2 - z_1}, \tag{11}$$

$$\lambda_n = \sqrt{\frac{n\pi}{\kappa P}} = \frac{\phi_n(z_1) - \phi_n(z_2)}{z_2 - z_1}. \tag{12}$$

Everett (1861) found small numerical differences between the two estimates from Eqs. (11) and (12), due to measurement error and to transient non-periodic components in the signal. Stallman (1965) showed that significant groundwater velocities moving heat energy in the vertical direction cause the two estimates of κ to differ significantly, and used this difference to infer water flow rate.

We use the air ground thermal orbit method of Beltrami (1996) to check the validity of the heat conduction assumptions. The monthly soil temperature was plotted against monthly air temperature, and elliptical phase-space orbits (or thermal orbit) should be observed with parameters that depend on the amplitude attenuation and the phase shift of the soil temperature.

4. Results and discussion

4.1. Analysis of Cowra soil and air data

Soil temperature data from 1972 to 2010 at the depths 0.1, 0.2, 0.5, 1 m and at 1.8 m from 1942 to 2010 (Fig. 2) was evaluated using Fourier analysis for the average values c_0 (Eq. (6)), and the first harmonic Fourier coefficients c_1 (Eq. (7)) and d_1 (Eq. (8)) with a period P of a year.

To check the assumption that soil heat is transported mostly by conduction, Beltrami (1996) proposed that monthly means of soil temperature at depth be plotted against monthly means of air temperature. We used a simple average of daily minimum and maximum air temperatures as an estimate of daily average air temperature. As explained by Smerdon et al. (2009), for simple conduction (Eqs. (2) and (3)), the temperature orbit should be close to an ellipse whose centre is determined by the averages of the air and 1.8 m soil temperatures, with the quantity $\lambda_1 z$ giving the phase shift and attenuation at the depth z, and hence the inclination of the major axis and the eccentricity of the ellipse in the Beltrami plot. Fig. 3 shows a modified Beltrami plot with the data being the differences between the monthly averages of air and soil temperatures and the relevant annual averages. The figure shows a simple elliptical orbit with noise similar to the orbits in Beltrami (1996), and demonstrates that the assumption of Fourier heat conduction in the soil applies.

Using data from 2 depths (z_1 = 0.5 m, z_2 = 1.8 m) and the calculated Fourier coefficients we found two estimates $5.9 \times 10^{-7}\,m^2\,s^{-1}$ and $6.8 \times 10^{-7}\,m^2\,s^{-1}$ of the thermal diffusivity κ respectively from Eq. (12) and the differences in phase and from Eq. (11) and the differences in the natural logarithms of the amplitudes. The two estimates are close, showing that there is no significant vertical advection of heat by water movement. The mean value $6.4 \times 10^{-7}\,m^2\,s^{-1}$ was taken as the best estimate of the soil thermal diffusivity κ. Baker and Baker (2002) analysed the temperature waves at the depths of 3.2, 6.4 and

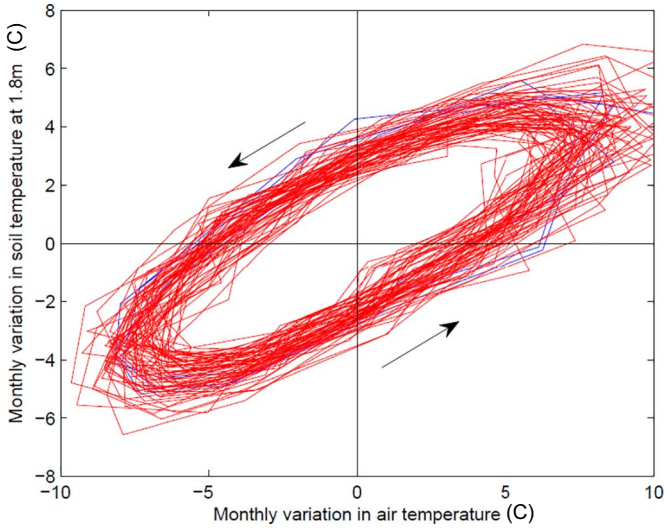

Fig. 3. Modified Beltrami plot of the deviations of the monthly averages at Cowra from the annual means, plotted against deviations of the monthly averages of the daily air temperature from the annual means, from 1942 to 2009. Data up to 1970 is shown in blue, later data in red. The arrows indicate the direction of the elliptical orbit. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

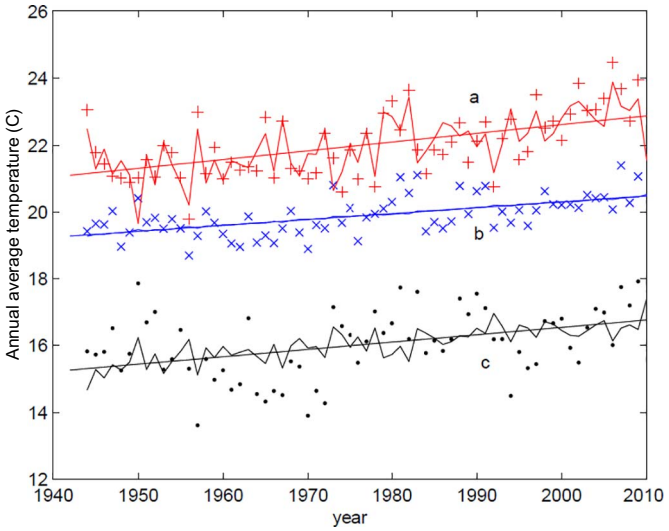

Fig. 4. The linear fits of the average annual air temperatures at Cowra against the annual rainfall and the year, for daily air temperature maximum T_{max} (a), minimum T_{min} + 10 C (b) and terrestrial daily minimum T_{terr} + 10 C (c). In each case, the straight line fit to year only is shown, together with the fit to both year and rainfall (connected line). Taking into account the rainfall improves the fit greatly for the temperature maximum, not at all for the air temperature minimum, and slightly for the terrestrial minimum.

12.8 m at their Minnesota site and estimated their κ to be 7.2×10^{-7} m^2 s^{-1} from the attenuation with depth. For heat transfer calculation purposes we choose a value of C of $2.5 \pm 0.25 \times 10^6$ J m^{-3} K^{-1} (mean ± std. deviation) for clay soils (Abu-Hamdeh, 2003) which is consistent with the range of values in Ochsner et al. (2001).

4.2. Soil temperature trends

First, a simple linear regression was fitted to the soil temperature at 1.8 m, giving a linear fit of the form $T(y) = 17.22 + 0.038(y - 1941)$, with y the year. The fitted rate of rise of 0.038 K yr^{-1} had a 95% confidence interval of [0.032, 0.044]. The average annual soil temperatures at depth 1.8 m, as plotted in Fig. 2, are consistent with the assumption that the soil temperature varied about a constant value from 1942 until about 1968, and then increased linearly until 2010 when the measurements ceased. Two separate linear regressions were done on the soil temperature from 1942 to 1968, and from 1968 to 2010. The fit up to 1968 is $T(y) = 17.801 + 0.0013(y - 1941)$, with a 95% confidence interval of [−0.021, 0.024] for the rate of rise. The rate of rise from 1942 to 1968 can therefore be taken to be effectively zero. From 1968 the linear fit is $T(y) = 16.186 + 0.0583(y - 1941)$, with a 95% confidence interval of [0.047, 0.070] for the rate of rise.

4.3. The effect of rainfall on soil and air temperatures

It has been observed in other countries (Zhao and Khalil, 1993; Trenberth and Shea, 2005; Bai et al., 2011) and in Australia (Ashcroft et al., 2014) that temperature variations can be correlated with rainfall variations. The annual rainfall at Cowra from 1944 to 2010 is shown in Fig. S3 in Supplementary materials. For the dry decade 2000–2009 the mean annual rainfall was 515.3 mm, followed by a wet year 2010 with rainfall more than double this at 1039.5 mm.

We investigated the effect of the amount of annual rainfall on annual soil temperature variation, as the analysis of Bai et al. (2011). We fitted linear models of the form

$$T_j = \beta + \gamma Y_j + \delta R_j \quad (13)$$

to the various mean annual temperatures T_j, where Y_j is the year and R_j is the annual rainfall in m for that year. The fitted coefficients γ and δ account for the long term trend and the effect of rainfall respectively.

Fig. 4 shows the fit of model Eq. (13) to the three air temperatures T_{max}, T_{min} and T_{terr}. The fitted annual rates of rise γ have the values 0.026, 0.0176 and 0.022 K yr^{-1} for T_{max}, T_{min} and T_{terr} respectively. The fitted values of δ, the change in annual temperature for change in annual rainfall, are −3.2, 0.1 and 1.6 K m^{-1} respectively. For the temperature maximum T_{max}, fitting the rainfall accounted for more than half of the residual sum of squares after the temporal trend was fitted, both fitted coefficients γ and δ are statistically significant ($p < 0.001$). The rainfall accounted for almost none of the variation in T_{min} and a small amount of the variation in T_{terr} ($p > 0.01$), as is evident in Fig. 4.

The model Eq. (13) was then fitted to the annual average soil temperatures at depths 0.1, 0.2, 0.5, 1.0 and 1.8 m for the years 1972 to 2010, and the results are shown in Fig. 5. The fitted coefficients γ of temperature rise for those depths were 0.033, 0.036, 0.068, 0.089 and

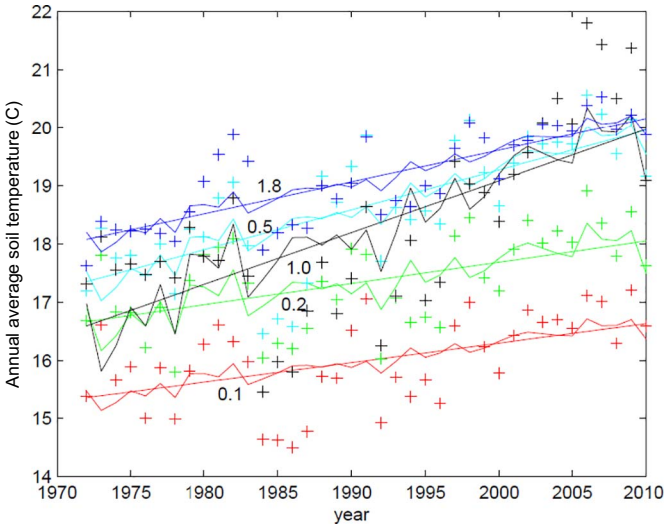

Fig. 5. Annual soil temperatures at Cowra at the depths 0.1, 0.2, 0.5, 1.0 and 1.8 m, showing the fitted regressions against year (straight line) and year and annual rainfall (connected line). The measured values are shown as '+' symbols.

0.055 K yr^{-1}, and all are statistically significant ($p < 0.001$). The coefficients δ of temperature change with annual rainfall were −0.6, −1.3, −1.0, −2.2 and −0.7 K m^{-1} respectively, and were not statistically significant ($p > 0.01$). Adding the rainfall does not have a significant effect. It appears from Fig. 5 that the temperature measurements at the depths of 0.1, 0.2, 0.5 and 1.8 m are in a progression which is consistent with heat flow theory, but that the measurements at 1 m are somewhat anomalous. For this reason we have not used the data at 1 m to estimate the thermal diffusivity.

4.4. Linear surface temperature rise

As soil temperature was measured at different depths (Table 1), it would be beneficial to estimate the soil surface temperature increase as a standard. Lesperance et al. (2010) showed that a linear increase in soil surface temperature gives rise to a delayed and slower temperature rise at any depth z. For a surface rate of rise of α (K s^{-1}),

$$T(0,t) = \alpha t. \tag{14}$$

Carslaw and Jaeger (1959) gave the corresponding subsurface temperature rise at depth z as

$$T(z,t) = \alpha t\left\{\left(1+\frac{z^2}{2\kappa t}\right)\operatorname{erfc}\frac{z}{2\sqrt{\kappa t}} - \frac{z}{\sqrt{\pi\kappa t}}\exp\left(-\frac{z^2}{4\kappa t}\right)\right\}. \tag{15}$$

The corresponding heat flux density $f(t)$ W m^{-2} at the soil surface is

$$f(t) = -k\frac{\partial T}{\partial z}\bigg|_{z=0} = 2C\alpha t\sqrt{\frac{\kappa}{\pi t}}. \tag{16}$$

The cumulative heat flux density $F(t)$ J m^{-2} at the soil surface is

$$F(t) = \int_0^t f(t)dt = \frac{4C\alpha t}{3}\sqrt{\frac{\kappa t}{\pi}}. \tag{17}$$

This energy is equivalent to the amount of energy required to raise uniformly the temperature of the top layer of soil to a depth $D(t)$ m by the amount αt (K), with

$$D(t) = \frac{4}{3}\sqrt{\frac{\kappa t}{\pi}}. \tag{18}$$

The uncertainties in thermal properties estimate of κ and C can be propagated in the calculation of the heat flux density F and depth D assuming a normal distribution. Taking soil thermal diffusivity κ value of $6.4 \pm 0.2 \times 10^{-7}$ m^2 s^{-1} (mean ± std. deviation) and C of $2.5 \pm 0.25 \times 10^6$ J m^{-3} K^{-1}, and α the surface temperature rise in degrees K per year, and the time t expressed in years, the cumulative heat flux can be calculated as $F(t) = 8.47 \pm 0.87 \times 10^6\, \alpha\, t^{3/2}$ J m^{-2}, with the equivalent penetration depth: $D(t) = 3.38 \pm 0.05\, t^{1/2}$ m.

The appropriate dimensionless time variable to study the influence of transient surface temperatures at a depth z is $\tau = \kappa t/z^2$, with a surface temperature $T_0(\tau) = \alpha z^2 \tau/\kappa$. Using the large and small argument approximations of Gautschi (1965) for the error function, Eq. (15) has the small time approximation

$$T(z,\tau) \approx \frac{8\alpha z^2}{\kappa}\sqrt{\frac{\tau^5}{\pi}}\exp\left(-\frac{1}{4\tau}\right)(1 - 12\tau + 180\tau^2 ...) \tag{19}$$

useful for $\tau < 0.14$ approximately. The large time approximation

$$T(z,\tau) \approx \frac{\alpha z^2}{\kappa}(\tau - 2\sqrt{\tau/\pi} + 1/2 - 1/(6\sqrt{\pi\tau}) + ...) \tag{20}$$

useful in the range $\tau > 0.4$. The series Eq. (20) shows that as time τ increases, the difference between the surface temperature and the temperature at depth z approaches $(\alpha z^2/\kappa)$ $(2(\tau/\pi)^{1/2} - ½)$, which increases indefinitely with τ. The ratio of this temperature difference to the surface temperature rise approaches $2/(\tau\ \pi)^{1/2} - 1/(2\tau)$, which slowly approaches zero for large τ.

For the Cowra value of soil thermal diffusivity of 6.4×10^{-7} m^2 s^{-1}, when the characteristic time τ has the value unity for each depth 1 m and 1.8 m, the corresponding time t is 18 days and 59 days respectively, so the large time approximation (Eq. (20)) is valid after about 8 days and 24 days respectively at those depths. From Eq. (20), at 1 m depth the ratio of the temperature rise to the surface rise is 0.92 after 10 years and 0.96 after 40 years, and at 1.8 m the ratios are 0.87 and 0.93 respectively. The average ratio between the rise at 1.8 m depth and the surface rise is approximately 0.87 over the first 40 years, which means that the discrepancy should be taken into account in the fitting of a linear trend to measurements at this depth.

4.5. Estimating surface temperature rise

The average annual soil temperatures at Cowra at depth 1.8 m, as plotted in Fig. 2, are consistent with the assumption that the surface temperature T_s was constant at a value T_0 from 1942 until a time t_1 about 1970, and then was increasing linearly from t_1 until 2010 at a rate α_1. For $t > t_1$ we assume that the annual average surface temperature is $T(0, t) = T_0 + \alpha_1(t - t_1)$. For $t < t_1$ we assume that $T(z, t)$, the annual average soil temperature at the depth z is T_0,

$$T(z,t) = T_0 \text{ for } t < t_1. \tag{21}$$

Given an assumed value of κ of 6.4×10^{-7} m^2 s^{-1} and a value of α, for $t > t_1$ we calculate the corresponding $T(z, t)$ from Eq. (15) as

$$T(z,\tau) = T_0 + \alpha_1(t - t_1)\left[\left(1+\frac{1}{2\tau}\right)\operatorname{erfc}\left(\frac{1}{2\sqrt{\tau}}\right) - \frac{1}{\sqrt{\pi\tau}}\exp\left(-\frac{1}{4\tau}\right)\right], \tag{22}$$

where now $\tau = \kappa\,(t - t_1)/z^2$.

We used a nonlinear least squares procedure to determine the fitted values of the parameters T_0, t_1 and α_1 by fitting Eqs. (21) and (22) for a depth z of 1.8 m to the observed annual average temperatures at depth 1.8 m. The fitted parameter values are $T_0 = 17.8$ K, $t_1 = 1968$ years and $\alpha_1 = 0.061$ K yr^{-1}. This value of α gives a rise in surface of 2.56 K over the 42 years from 1968 to 2010, and a value of 16.6 MJ m^{-2} for the resultant extra energy in the soil at the end of the period. The corresponding penetration depth $D(t)$ is 21.9 m in 2010. Fig. 5 shows the fitted average temperature rise at a depth of 1.8 m and the corresponding surface temperature rise. For comparison, a simple linear regression of the annual average temperatures from 1942 to 2010 at depth 1.8 m is also shown, with the form $T = 17.2 + 0.038(Y - 1940)$, where Y is the time in years. The above estimates of rate of rise of soil temperatures and soil surface temperature ranging from 0.038 to 0.061 K yr^{-1} are certainly higher than the rates of rise of T_{max} of 0.026 and T_{min} of 0.018 K yr^{-1} found earlier for the maximum and minimum temperatures at 1.5 m above ground. Nevertheless soil temperature increase > 0.06 K yr^{-1} have been reported in the literature (Table 1), e.g. in the Mojave desert (Bai et al., 2014) and in Tatra Mountains in Poland and Slovakia (Gądek and Leszkiewicz, 2012).

4.6. Soil and air temperature rise at other locations

Soil temperature data from Gunnedah and Inverell in New South Wales and Brigalow in Queensland were analysed. The annual averages of daily soil temperatures at Gunnedah and Inverell at 9.00 AM at depths of 10 cm, 20 cm, 50 cm and 1 m from 1966 to 2012 are shown in Fig. 6. As at Cowra, the 9 am temperatures are lower closer to the soil surface. At all depths the soil temperatures at Gunnedah are about 2 C warmer than those at Inverell. Because the measured temperature records at shallower depths were incomplete, the same value of soil thermal diffusivity as at Cowra, $\kappa = 6.4 \times 10^{-7}$ m^2 s^{-1} was assumed. We assumed a linear increase in surface temperature from 1966 and fitted the calculated temperature rise at 1 m from Eq. (22) to the 1 m data at Gunnedah from 1966 to 2012 and at Inverell from 1974 to 2011.

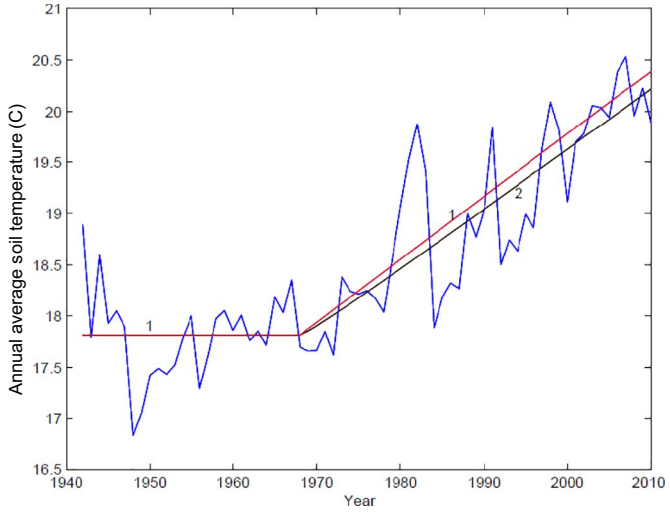

Fig. 6. Fitted soil temperatures at Cowra at depth 1.8 m calculated from Eqs. (21) and (22), plotted against time in years. Curve 2 is fitted to the observed annual average values at depth, and curve 1 is the corresponding surface temperature rising after 1968 at a rate of 0.061 K yr^{-1}.

Compared to Cowra, the shallower depth of 1 m reduces the difference between surface temperature and temperature at depth. The fitted values for surface temperature rise at both Gunnedah and Inverell were 0.02 K yr^{-1}, and the fitted lines are shown in Fig. 6. The fitted average surface temperature at Gunnedah is warmer than at Inverell by nearly 2 C.

The data for daily minimum and maximum air temperatures at Gunnedah from 1970 to 2012 were also analysed. Linear regressions were done, giving fits of $T_{min} = 11.8 + 0.019(year - 1965)$ and $T_{max} = 24.0 + 0.023(year - 1965)$ respectively. These annual rates of rise of 0.019 and 0.023 K yr^{-1} are comparable to the fitted rate of rise of the surface temperature of 0.02 K $year^{-1}$. Calculations were not done for Inverell because there are major gaps in the daily minimum and maximum air temperature data.

For the Brigalow site, available annual averages of daily soil temperature data at 9 am for the depths of 50 cm and 1 m from 1969 to 2010 inclusive is shown in Fig. 7, together with simple linear fits to the data. The fitted rates of annual increase in temperature are 0.022 K yr^{-1} at both depths. The annual averages of the daily minimum T_{min} and daily maximum air temperatures T_{max} are plotted, together with simple linear fits to the data (Fig. 8). The fitted rates of

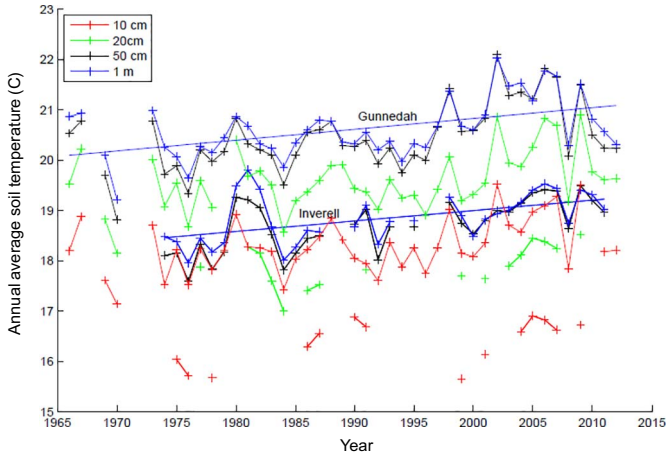

Fig. 7. Fitted soil surface temperatures for Gunnedah and Inverell calculated from Eqs. (21) and (22), plotted against time in years. Both locations give a fitted surface temperature rise of 0.02 K yr^{-1}.

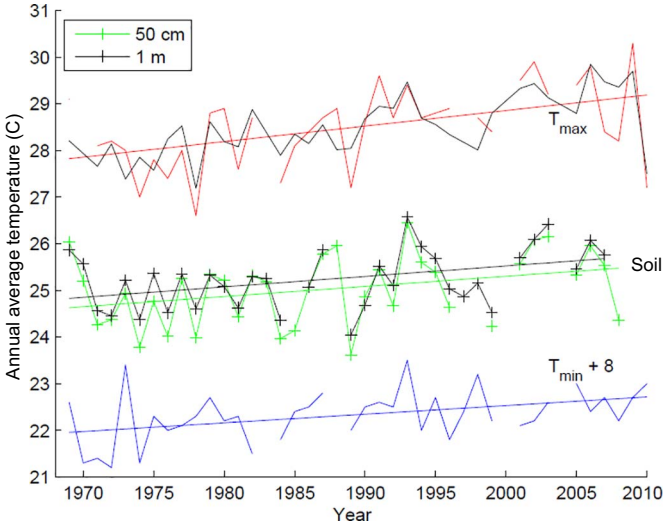

Fig. 8. Fitted annual averages of daily minimum and maximum air temperatures, and 9 am soil temperatures at 50 cm and 100 cm depths for Brigalow, plotted against time in years, with 8 C added to the minimum values for ease of comparison. The annual rates of rise of the fitted minimum and maximum air temperature, and the soil temperatures at 50 and 100 cm are 0.019, 0.033, 0.022 and 0.022 K yr^{-1} respectively.

rise are 0.019 and 0.033 K yr^{-1} respectively. The estimated thermal diffusivity was 4.0×10^{-7} m^2 s^{-1}, and the fitted value for surface temperature rise at Brigalow was at 0.021 K yr^{-1}.

The Australian Bureau of Meteorology (BOM) has published figures for the annual average temperature anomaly for Australia. We downloaded the annual average temperature anomaly data for 1942 to 2010, and fitted a linear regression to the temperature anomaly averages for the three periods from 1968 to 2010, from 1942 to 1968, and from 1968 to 2010 (Supplementary Material, Fig. S9). Over the whole period the fit gave a temperature rise of 0.0139 K yr^{-1}, with a 95% confidence interval of [0.0101, 0.0178]. Over the earlier and later periods, the fitted rates of rise were 0.0108 and 0.0179 K $year^{-1}$ respectively, with 95% confidence intervals of [−0.0048, 0.0264] and [0.0097, 0.0261] respectively.

As a comparison, Baker and Baker (2002) found a soil temperature rise of between 0.045 and 0.048 K $year^{-1}$ from 1963 to 2000 at their Minnesota site, with an air temperature rise of 0.049 K $year^{-1}$ over the period.

4.7. Assumptions and implications

The analysis of this paper assumed a one dimensional heat conduction model. In addition, we assumed a constant thermal diffusivity, and a value of thermal capacity throughout the profile. We realise potential measurements error, non-periodic temperature trend, and vertical water flow that may influence the results. Nevertheless we tried to include uncertainties of the estimates in the calculation.

We quantify changes to heat storage in the soil profile, and increased soil respiration and nitrous oxide generation due to the 0.061 K yr^{-1} soil temperature rise at Cowra, and the 0.02 K yr^{-1} rises at Gunnedah, Inverell and Brigalow over 4 decades. These soil temperature rise is similar to what has been reported worldwide (Table 1).

Using the average soil thermal diffusivity and capacity, the extra heat storage due to a linear temperature rise can be calculated using Eq. (17). Assuming a normal distribution, the uncertainty of thermal properties was propagated in the calculation. Over 40 years this is $12.8 \pm 1.3 \times 10^8$ J m^{-2} at Cowra and $4.3 \pm 0.4 \times 10^7$ J m^{-2} at Gunnedah, Inverell, and Brigalow. Baker and Baker (2002) calculated an annual heat flux of 1.1 MJ m^{-2}, and Beltrami et al. (2002) calculated a net global average heat flux of 1.2 MJ m^{-2} yr^{-1} for the period of 1950–2000. This value is comparable with Gunnedah, Inverell, and

Brigalow ($1.075\ MJ\ m^{-2}\ yr^{-1}$) but smaller than in Cowra ($3.25\ MJ\ m^{-2}\ yr^{-1}$).

The effects of temperature changes on soil respiration were studied by Lloyd and Taylor (1994) and Kirschbaum (1995). The conventional assumption for both respiration and nitrous oxide generation is that the reaction rate depends exponentially on temperature, with modifications due to various feedback effects (Davidson et al., 2006). If R_1 and R_2 are the reaction rates at temperatures T_1 and T_2 respectively, then

$$R_2 = R_1 \exp(0.1 \log(Q_{10})(T_2 - T_1)) \quad (23)$$

where the parameter Q_{10} is about 2. According to Eq. (23), over 40 years the soil temperature rises of 2.44 K at Cowra and 0.8 K at Gunnedah, Inverell, and Brigalow will cause increases in the reaction rates for the greenhouse gases carbon dioxide and nitrous oxide of 18% and 5.7%, respectively.

5. Conclusions

We have analysed the soil temperature data recorded up to about 2010 at four locations in eastern Australia, and all show clear evidence of a warming trend from about 1970. The measurements at around 1.8 m at Cowra from 1942 to 2010 show a clear warming trend overall, and a steep rise after about 1970. Accounting for the attenuation and delay of the surface temperature signal with depth, we have estimated the corresponding rise of the soil surface temperature at Cowra from about 1970 as $0.06\ K\ yr^{-1}$. From 1971 the temperatures at shallower depths were also measured, and these also show a temperature rise. The average soil temperature at depth is determined by the average soil surface temperature, which is affected by the surface air temperature and the solar radiation. Unfortunately, for comparison we only have the daily maximum and minimum temperatures at 1.5 m, and the daily terrestrial minimum air temperature measured at the top of the blades of grass. The air temperatures show a lower rate of rise, with the rate of rise of the average of the daily maximum and minimum being $0.022\ K\ yr^{-1}$. We analysed the effect of rainfall on temperature, and found that wet days had significantly less daily variation in temperature than dry days. The daily maximum temperature was significantly lowered by rainfall, and the annual soil temperatures were only slightly affected by annual rainfall. In particular, it is likely that the observed dip in the air and soil temperatures at Cowra in 2010 was caused by the very high rainfall that year.

At Gunnedah, Inverell, and Brigalow from about 1970 the rises in the air temperature and the soil temperatures at 1 m were all around $0.02\ K\ yr^{-1}$. These values are similar to the estimated temperature rise from the Bureau of Meteorology temperature data for the whole of Australia of about $0.018\ K\ yr^{-1}$ from 1968 to 2010. The Cowra data series is unusual in starting around 1942, whereas other Australian data sets generally start around 1970. The differences between the soil temperature rises at Cowra and those at Gunnedah, Inverell and Brigalow indicate that long term trends should be investigated at other Australian sites with soil temperature data.

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JHK has benefited from helpful discussions with Freeman Cook. The daily weather data and soil temperature data for Inverell, Gunnedah, Brigalow and some depths at Cowra is available from www.bom.gov.au, the website of the Australian Bureau of Meteorology. The rest of the Cowra soil temperature data is available from Terry Koen of the Office of Environment and Heritage, New South Wales.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2017.11.015.

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